

# Indirect Determination of Cross Sections for Astrophysics

Thomas Rauscher  
University of Basel  
Switzerland

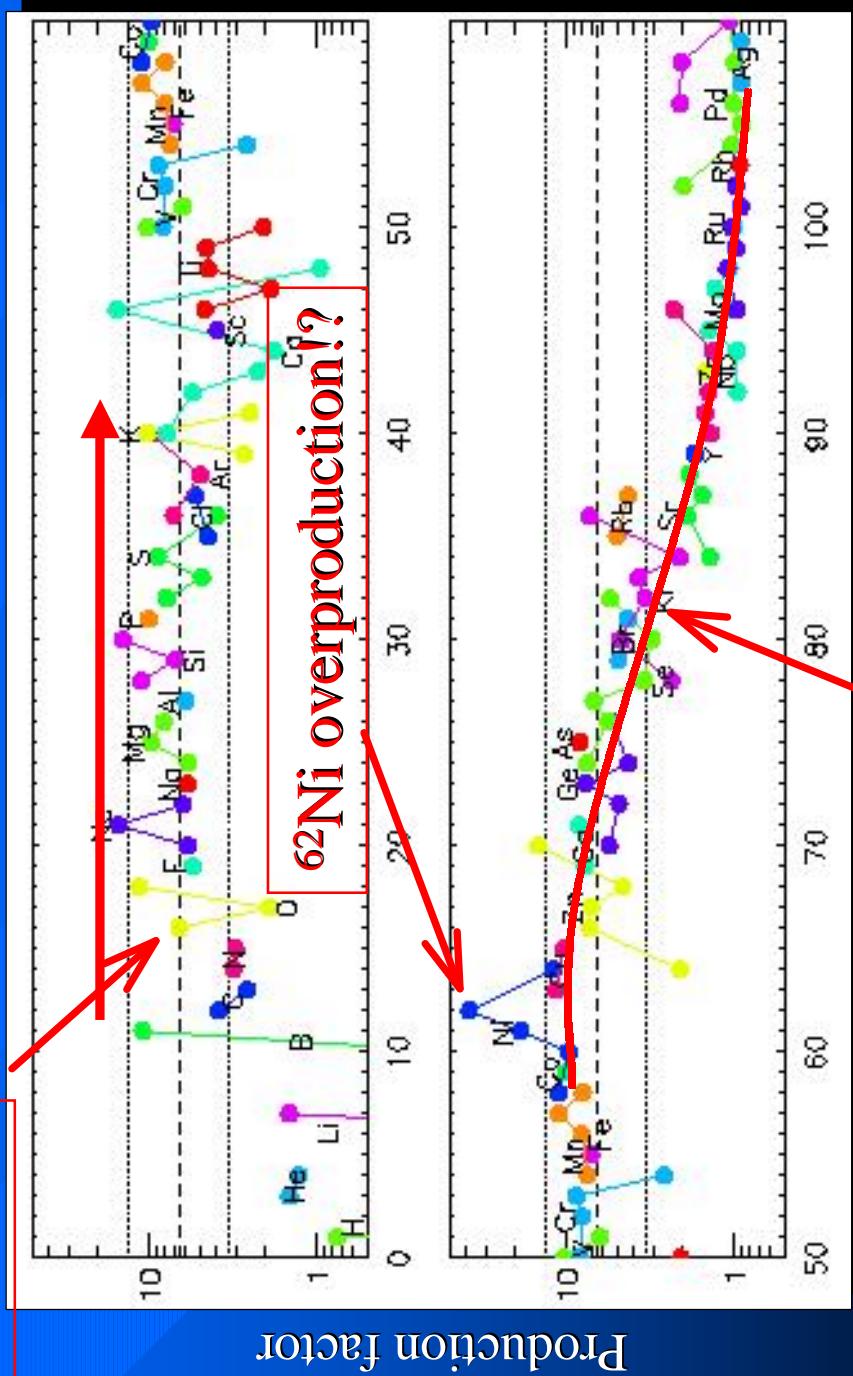
# Outline

- Astrophysical Motivation
- Relevant Energies and Reaction Mechanisms
- Interesting Nuclear Properties
- Selected Examples
- Summary

# Nucleosynthesis Results ( $15 M_{\odot}$ )

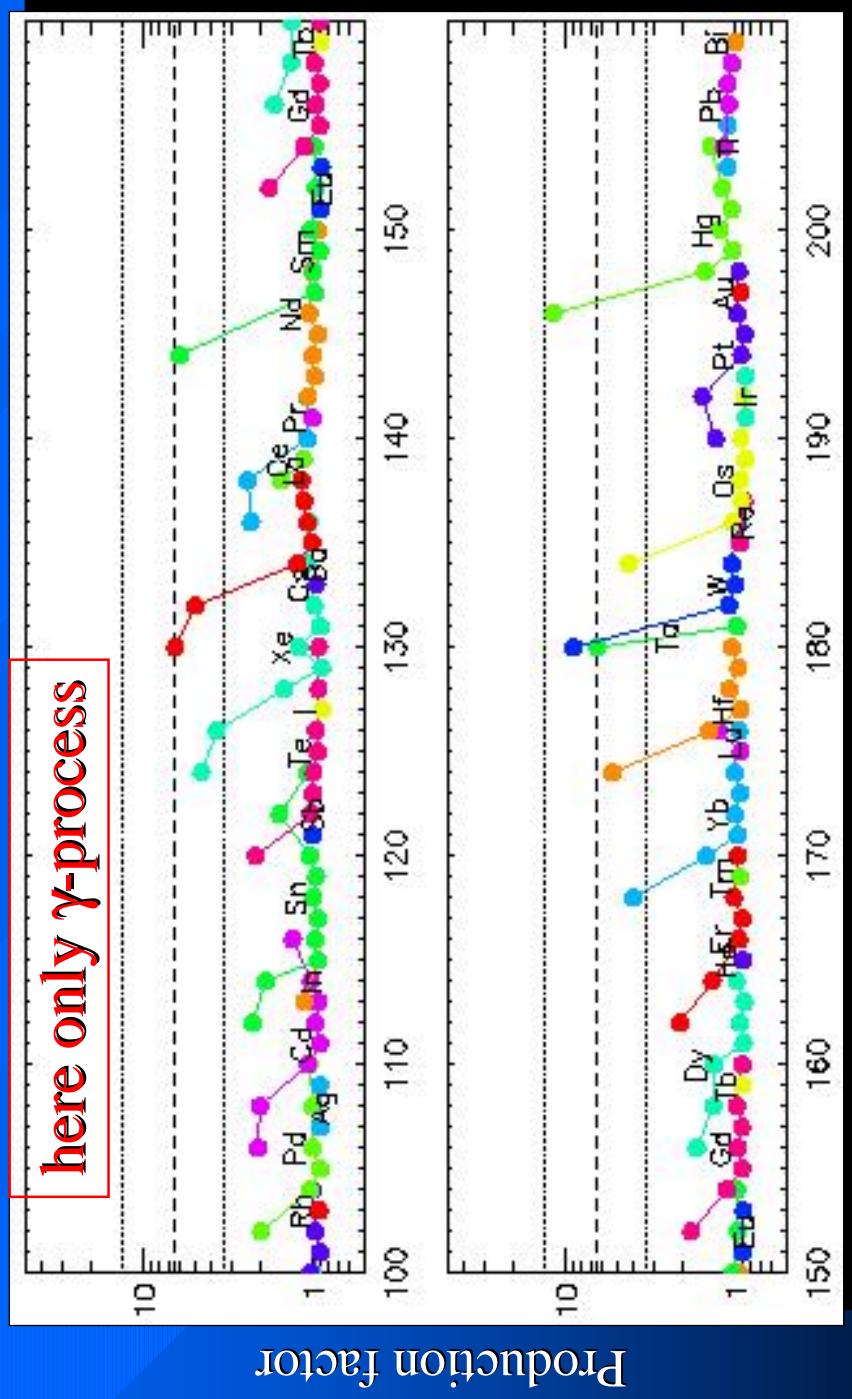
$^{16}\text{O}$  is indicator

Mostly hydrostatic burning



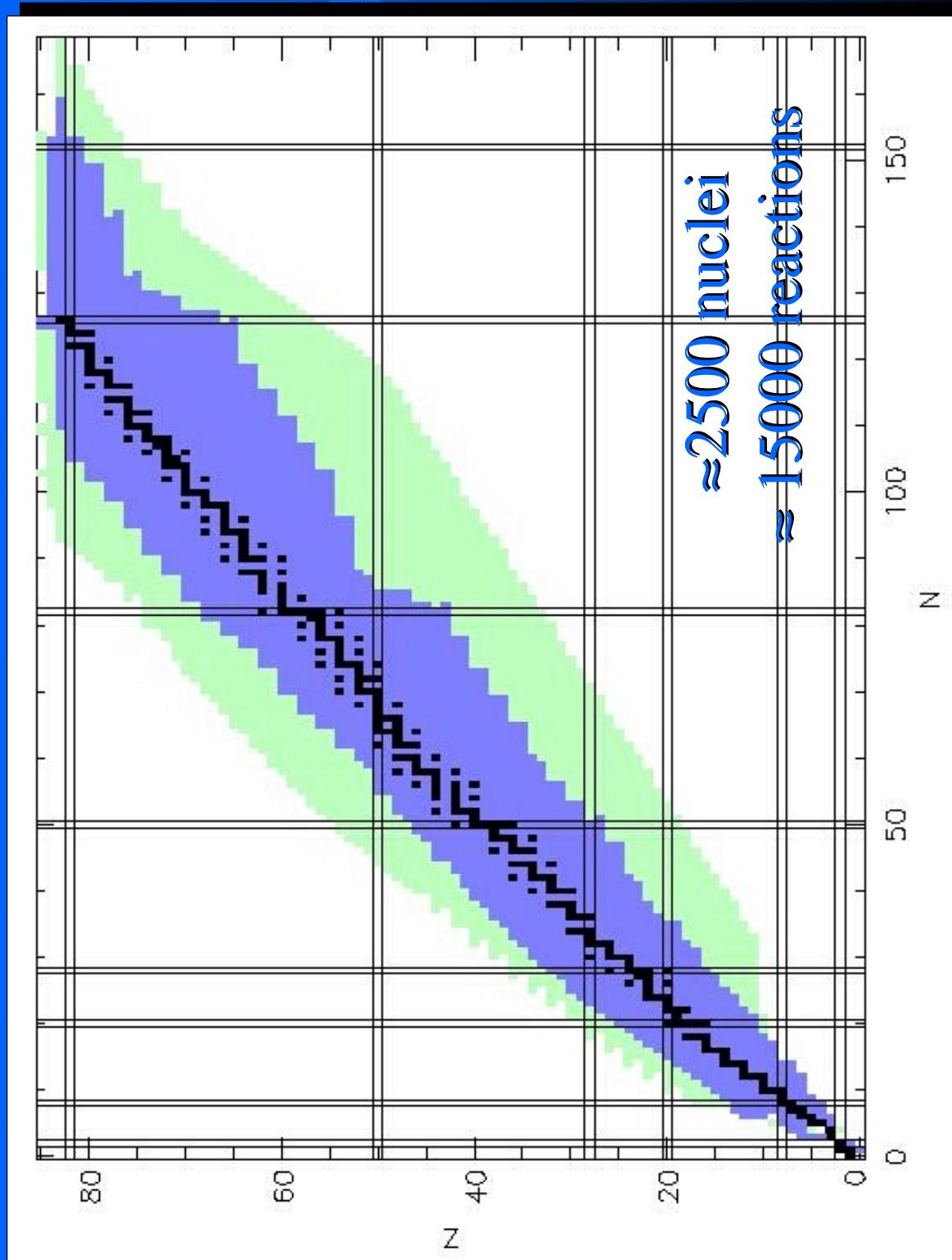
Rauscher et al. 2002 (with UCSC and LLNL)

# Nucleosynthesis Results ( $15 M_{\odot}$ )



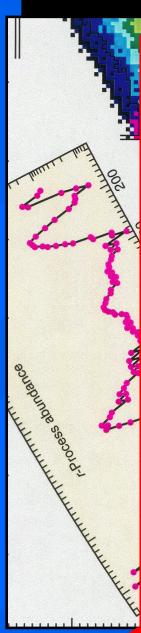
Rauscher et al. 2002 (with UCSC and LLNL)

# The Full Network



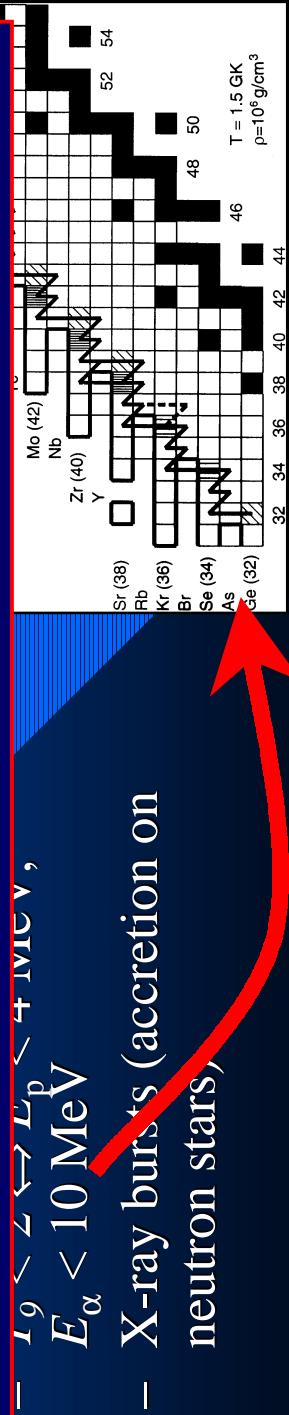
# Typical Conditions

Extremes:



These paths are defined by equilibria:  
only need separation energies,  $\beta$ -decays!

If abundances can be altered in freeze-out:  
need reaction rates (all properties)



# Waiting Point Approximation

Assuming  $\lambda_\beta \ll \lambda_n$  (r-process):

$$dY_{(Z,A)}/dt = \lambda_{\gamma(A+1)} Y_{(Z,A+1)} - n_n <\sigma v>_{n\gamma(A)} Y_{(Z,A)}$$

In  $(n, \gamma) \leftrightarrow (\gamma, n)$  equilibrium  $dY/dt = 0$  and

$$Y_{(Z,A+1)}/Y_{(Z,A)} = n_n <\sigma v>_{n\gamma(A)} / \lambda_{\gamma(A+1)}$$

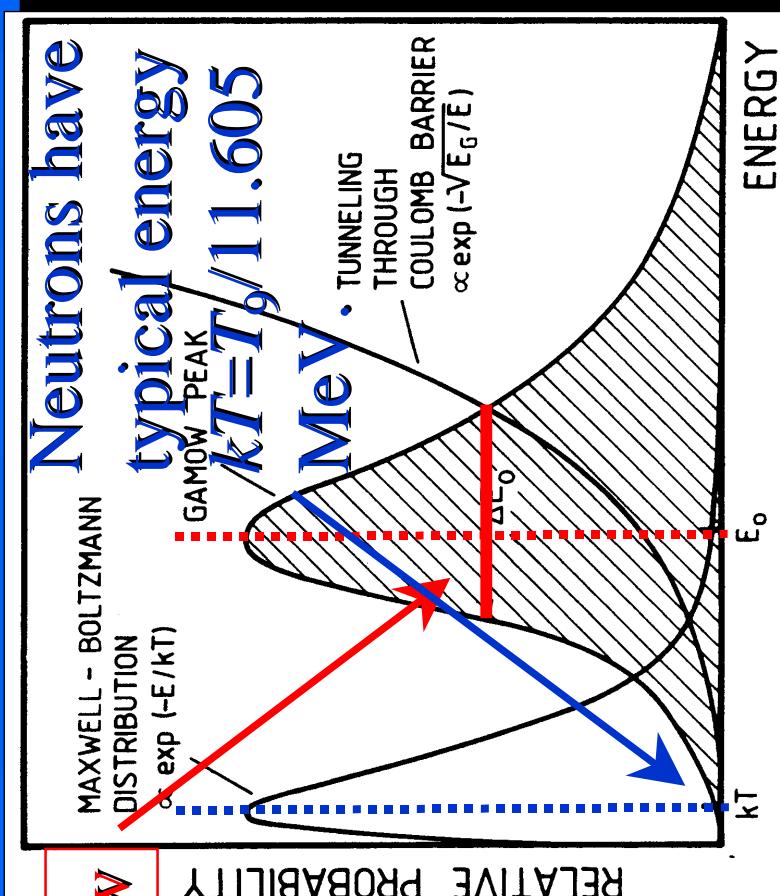
Applying detailed balance yields:

$$\frac{Y_{(Z,A+1)}}{Y_{(Z,A)}} = n_n \frac{G_{A+1}}{2G_A} \left( \frac{2\pi\hbar^2}{\mu kT} \right)^{3/2} e^{-(A+1)S_n/kT}$$

Parameters  $n_n, T$ , r-process path located around  $S_n = 2-3$  MeV.

# Reaction Rate (MB) Per Particle Pair

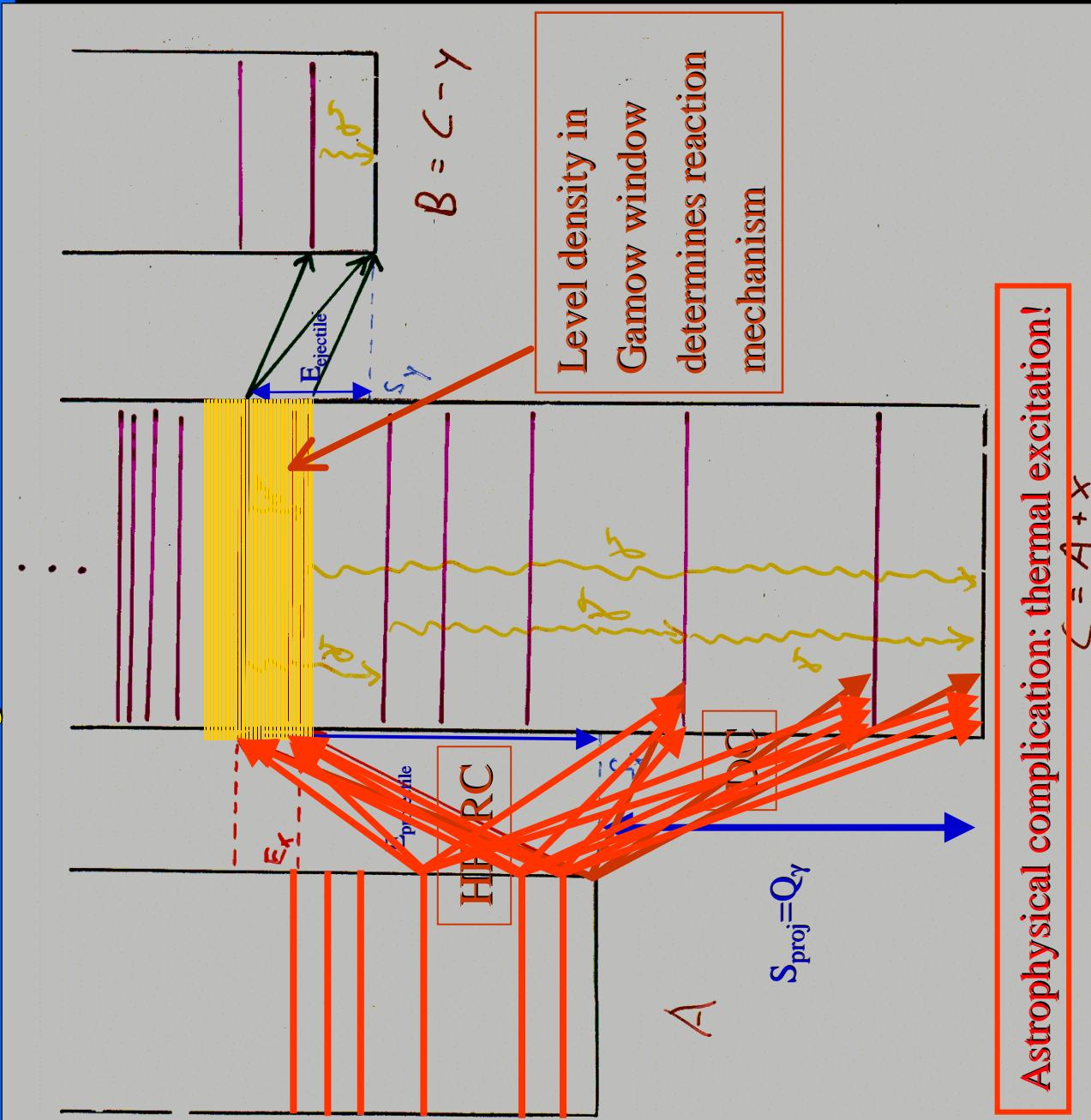
Gamow window



Rolfs & Rodney 1985

$$\langle \sigma^* v \rangle = \sqrt{\frac{8}{\mu\pi}} \frac{1}{(kT)^{3/2}} \int_0^\infty E \sigma^*(E) e^{-E/kT} dE$$

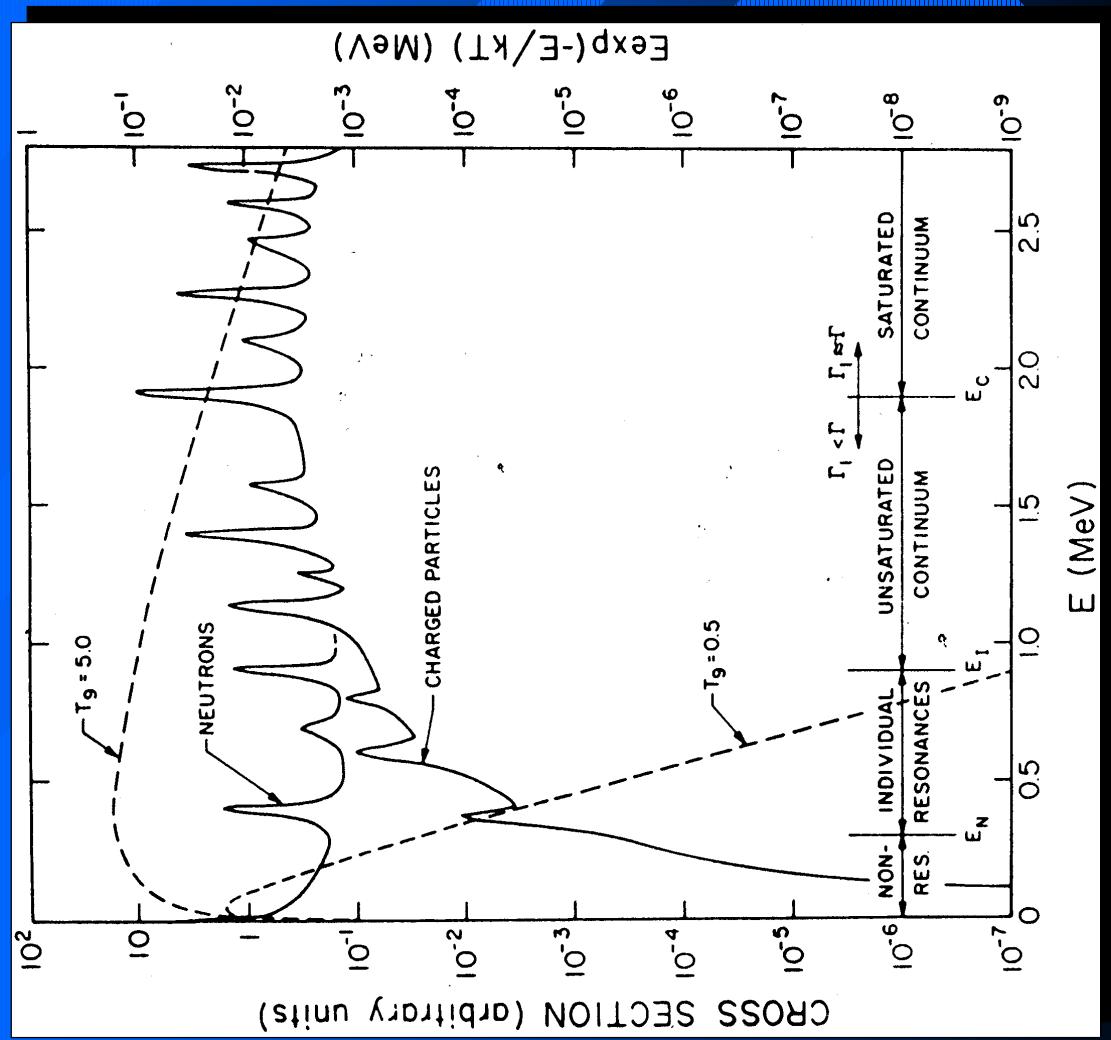
## Energetics in Nuclear Reactions



# Reaction Mechanisms I

## Regimes:

1. Overlapping resonances  $\Rightarrow$  statistical model (Hauser-Feshbach)
2. Single resonances  $\Rightarrow$  Breit-Wigner, R-matrix
3. Without or in between resonances  $\Rightarrow$  Direct reactions



# Portion of Direct Capture in Cross Section



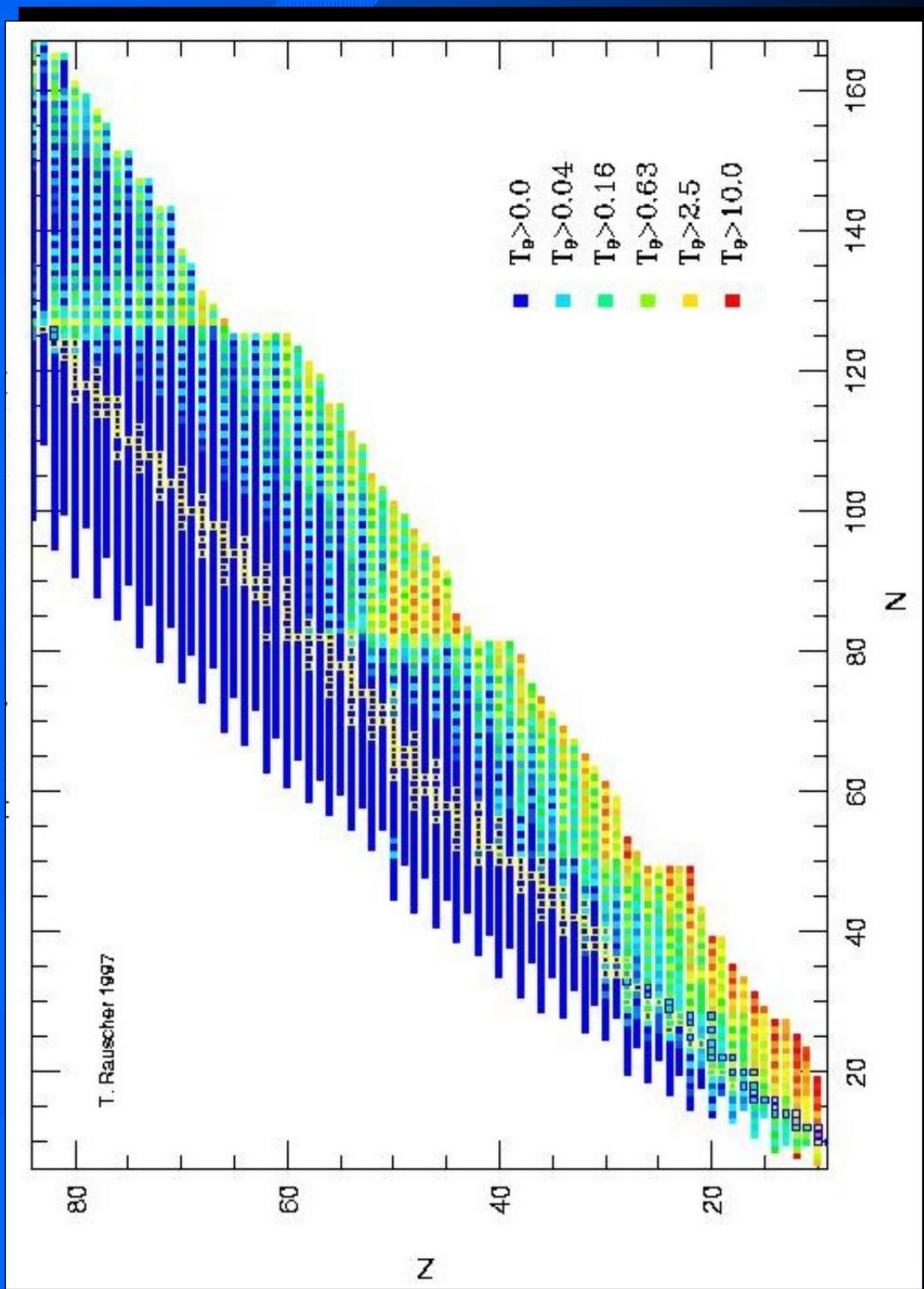
$^{50}\text{Ti}$  is stable  
( $N=28$ )

decreasing  $S_n$

Rauscher 1995

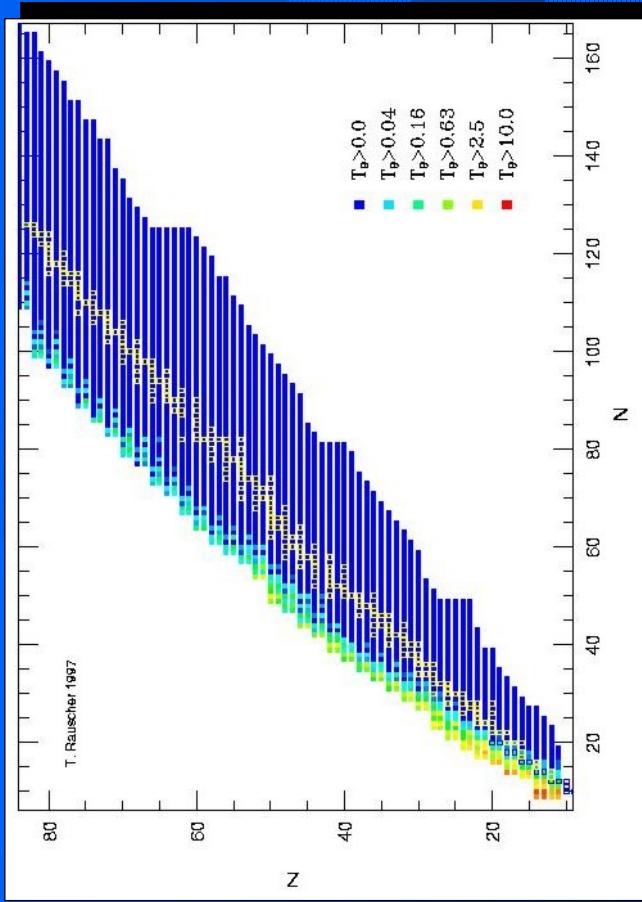
# Applicability of the Statistical Model

Neutron induced reactions

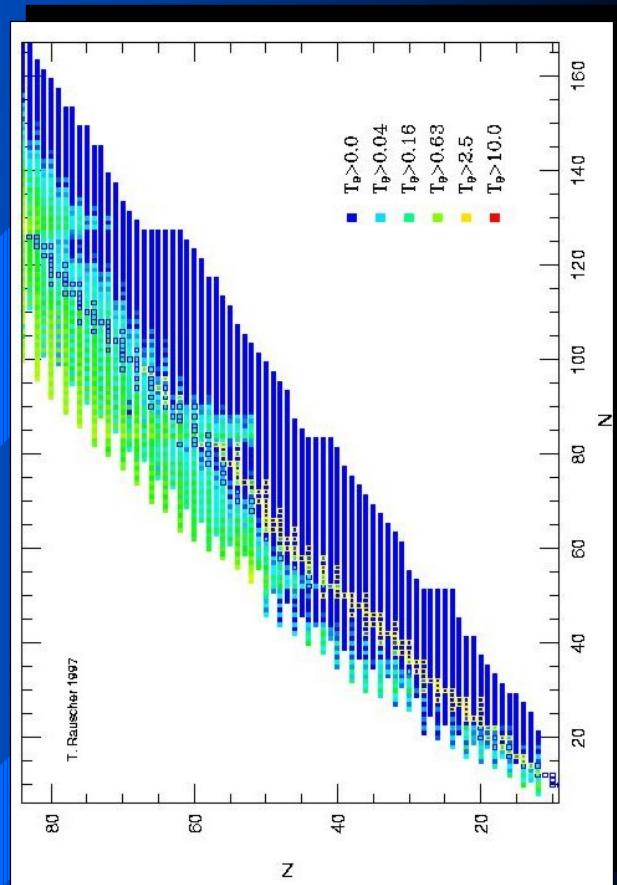


Rauscher et al. 1997

# Applicability of Statistical Model



$\alpha$ -induced reactions



Proton induced reactions

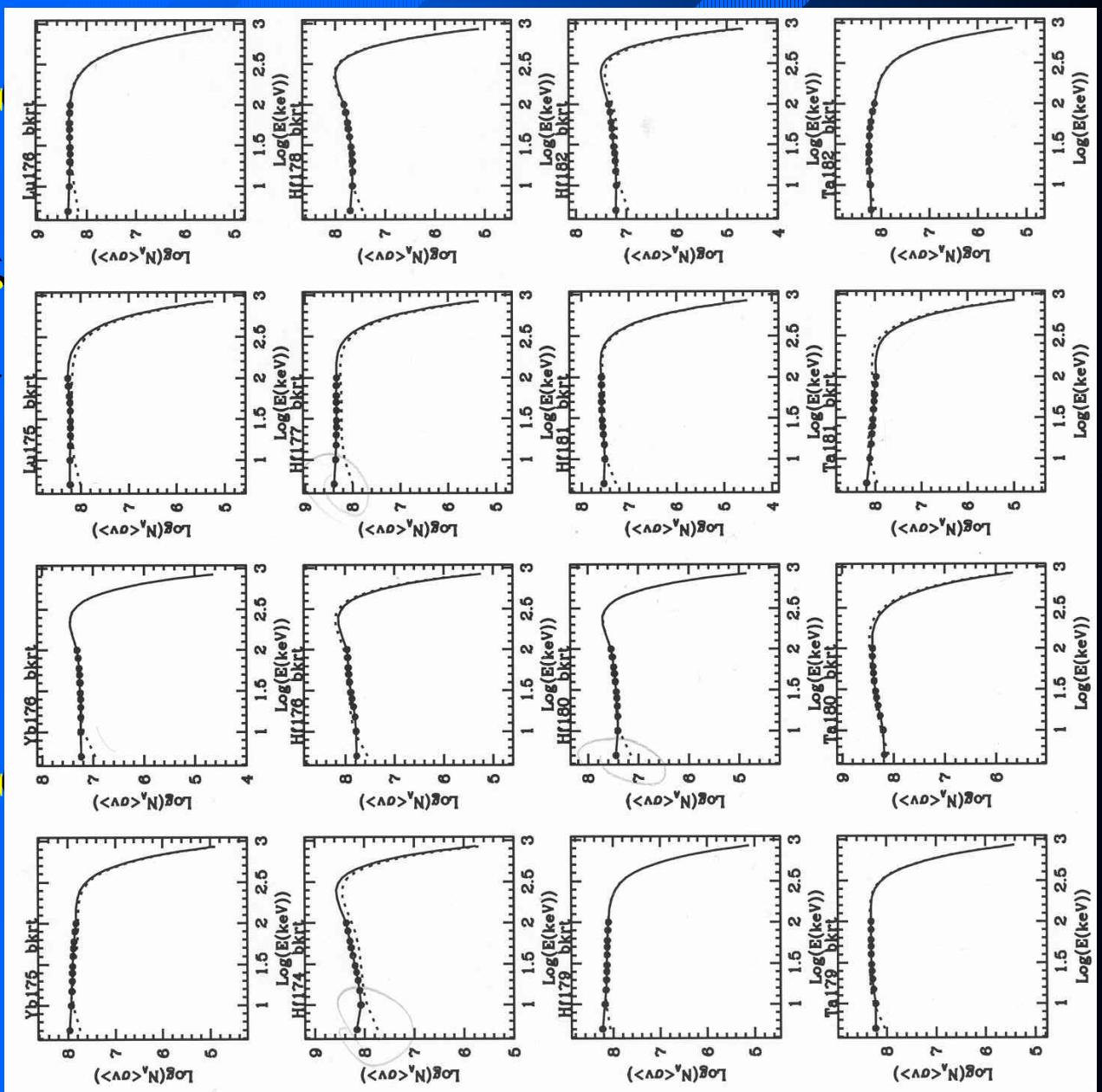
Rauscher et al. 1997

# Reaction Rates From The Statistical Model

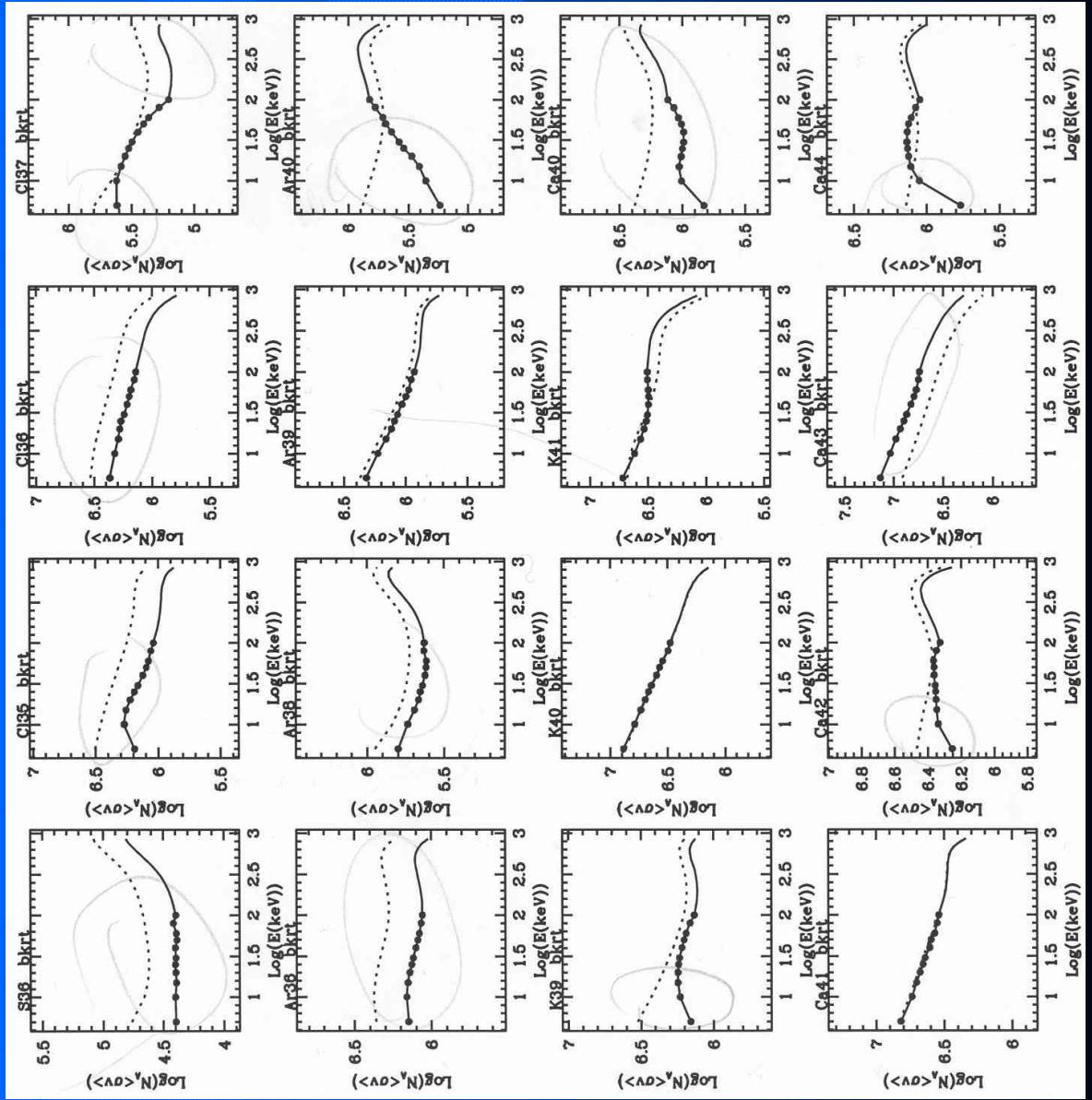
- Standard rates from NON-SMOKER code
- Rate library with fits  
(5000 targets, 30000 reactions)  
Rauscher & Thiedemann, ADNDT 75 (2000) 1
- Temperature/Energy applicability limits given!!
- Tables of rates, cross sections, inputs  
Rauscher & Thiedemann, ADNDT 79 (2001) 47
- Available on-line  
ADNDT web site or  
<http://nucastro.org/reaclib.html>

# Comparison to $(n, \gamma)$ Experiment I

- Exp: Bao et al. 2000
- Theo: Rauscher & Thielemann 2000



# Comparison to $(n,\gamma)$ Experiment II



# Interesting Nuclear Properties

(in no particular order!)

## Nuclear level density (stat., mod., input), low-lying states

- Systematics

- Shell quenching?

- Masses (Q-values, sep. energies, equilibria path location)

## Optical Potentials (stat., mod., imp., DC)

### ■ Giant resonances (stat. mod. inp.)

- Low energy behavior

- Pygmy Resonances?

- Nucleon density distribution  
(deformation, neutron skin)

■ Fission barriers

## Reaction mechanisms, cross sections

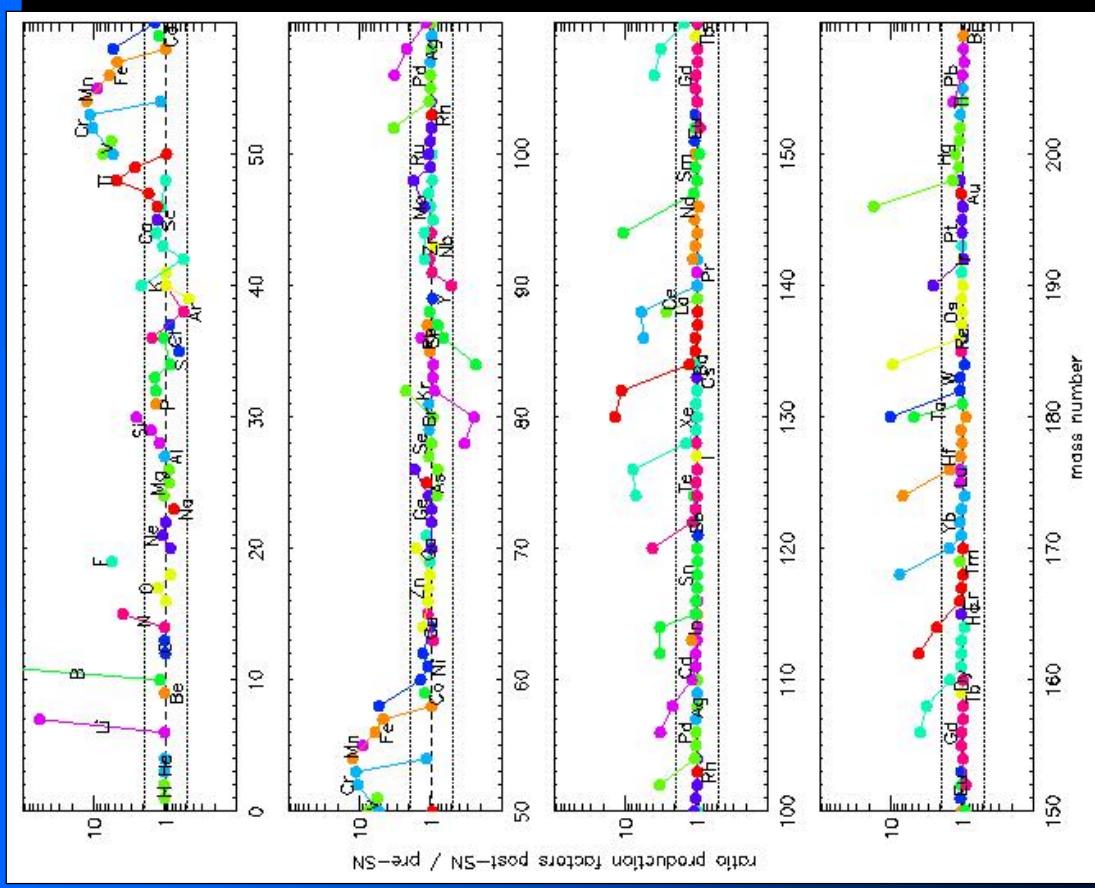
- $\beta$ -decay (time scales), weak rates (collapse and explosion)

# $\alpha$ Potentials in the $\gamma$ -Process

Yannick Heiter  
University of Bonn

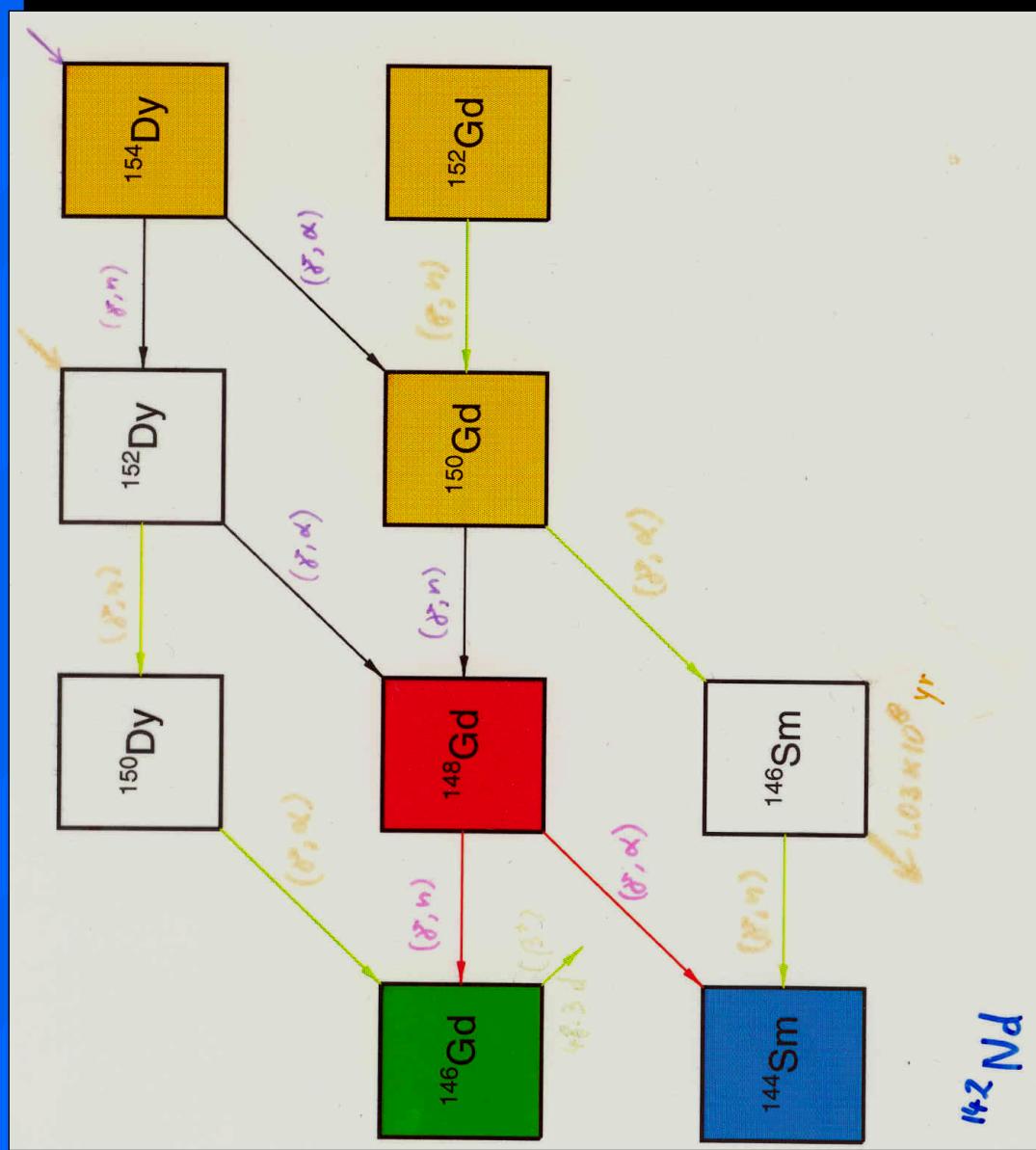
# Explosive Nucleosynthesis

- Li, Be, F from  $\nu$ -burst
- Ti-Fe by high n-flux
- $\gamma$ -Process (depending on mass/stellar structure)

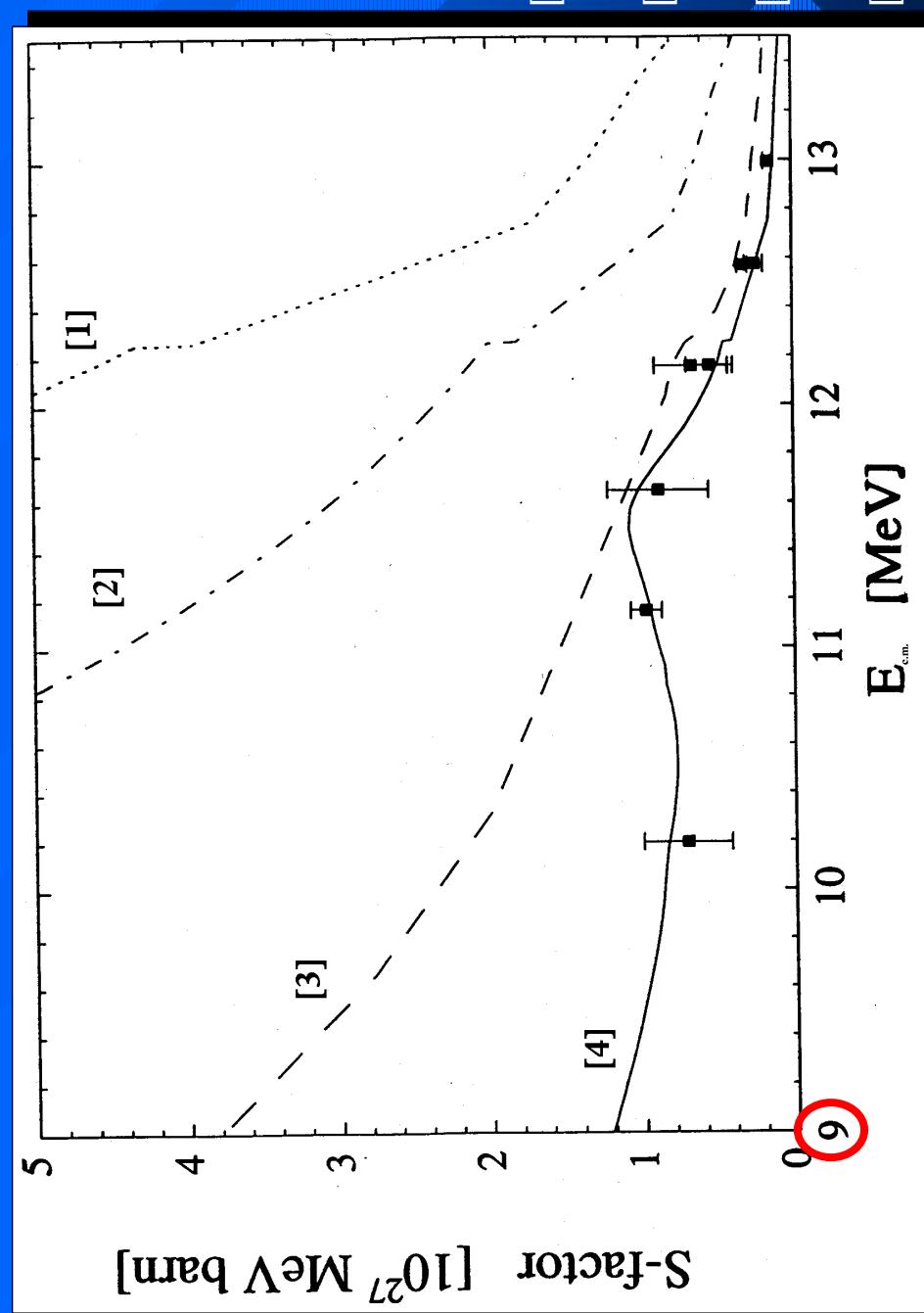


Rauscher et al. 2002 (with UCSC and LLNL)

# The $\gamma$ -Process



# Problem with $\alpha$ +Nucleus Potentials

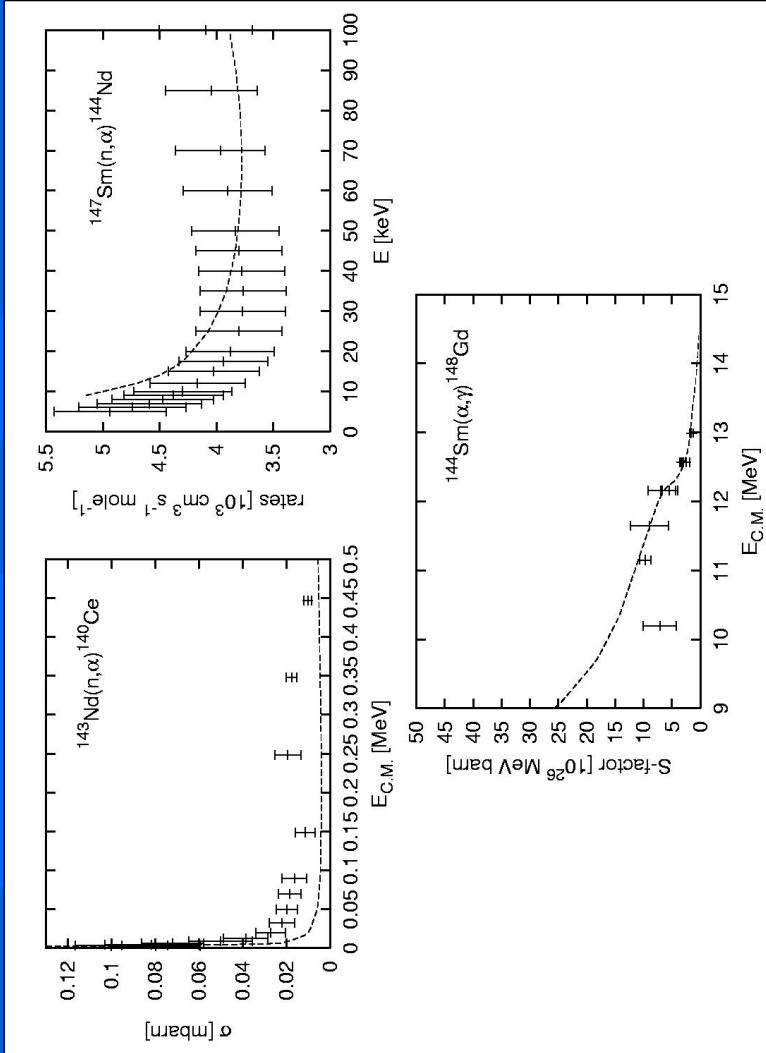


$^{144}\text{Sm}(\alpha, \gamma)^{148}\text{Gd}$

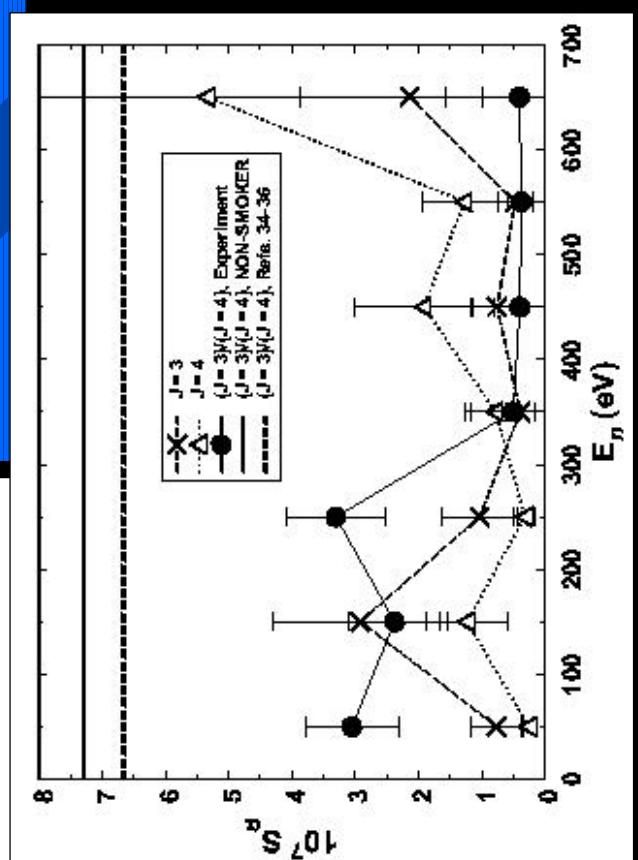
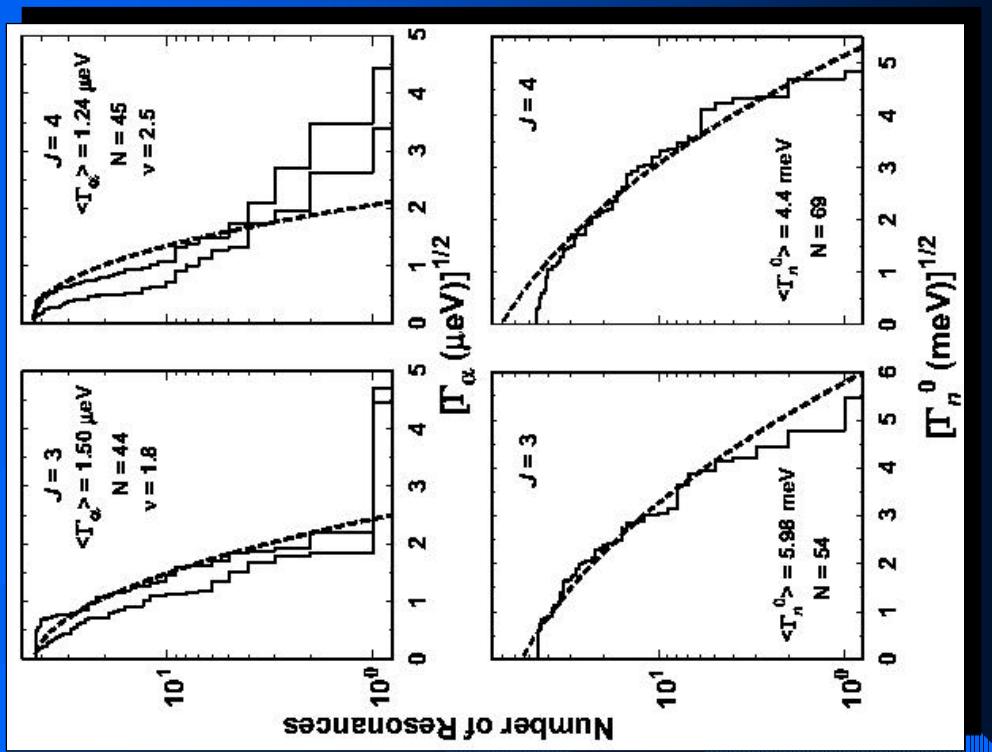
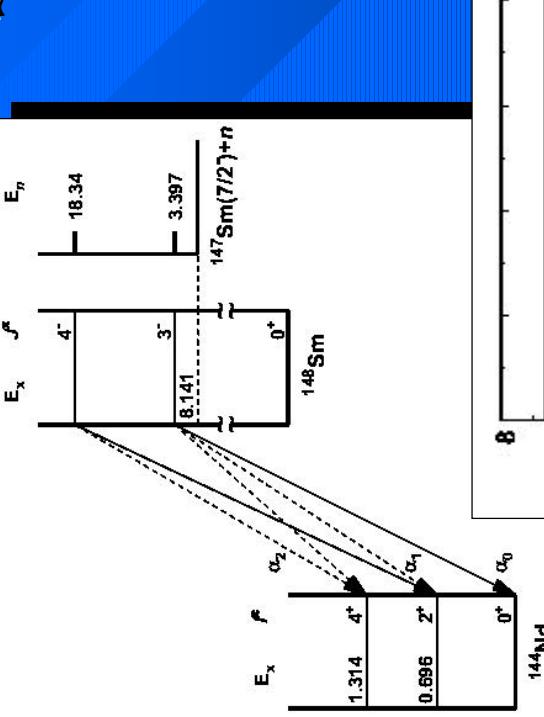
- [1] McFadden & Satchler Pot.
- [2] Avrigeanu Pot.
- [3] Mohr & Rauscher 98 Pot.
- [4]+exp: Somorjai et al. 1999

# Non-Statistical Effects in Optical $\alpha$ -Potentials?

- Series of ( $n, \alpha$ ) measurements (Oak Ridge NL)
- Found new, simple, global potential, but:  
 $^{147}\text{Sm}(n, \alpha)$  always problematic.
- Koehler et al. (2003) find, resonances in  
 $^{148}\text{Sm}$  non-statistically distributed.



# Non-Statistical Effects in $^{147}\text{Sm}(\text{n},\alpha)^{144}\text{Nd}$

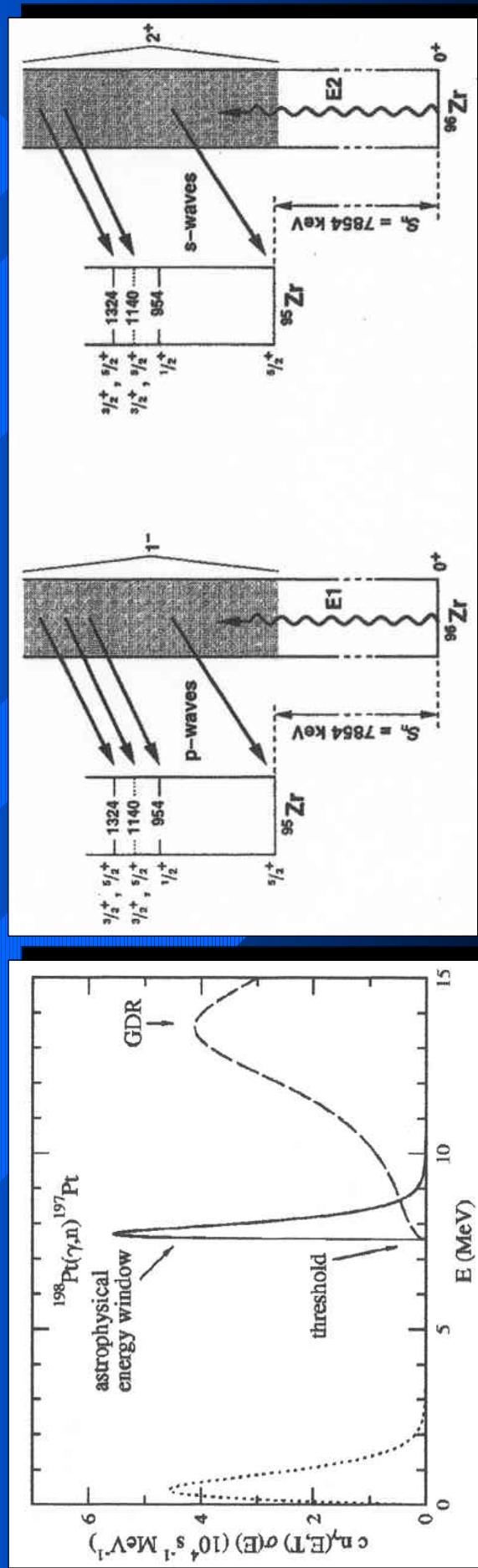


# Photodisintegration studies for the $\gamma$ - and the S-process



# Simulating Photodisintegration

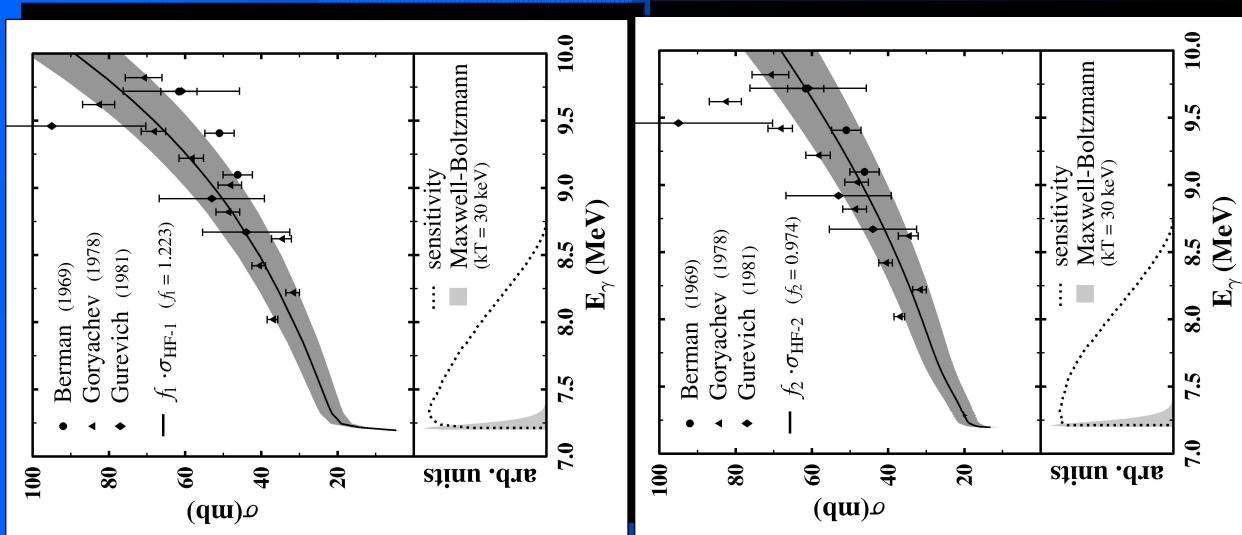
- Bremsstrahlung spectra or mono-energetic
- Simulate Photon-Bath by superposition
  - Can only probe ground-state transition: unrealistic rate
- Tests only few transitions!



Mohr et al. 2001, Vogt et al. 2003, Sonnabend et al. 2003

# $^{186}\text{W}(\gamma, \text{n})^{185}\text{W}$

- $^{185}\text{W}(\text{n}, \gamma)$  is important in S-process branching,  $^{185}\text{W}$  unstable
- $(\gamma, \text{n})$  can test prediction of ground state  $\gamma$ -transition
- Rescaling of  $(\text{n}, \gamma)$  according to  $(\gamma, \text{n})$  result



# ISOTOPES in S-Process Branchings

(1)	$^{63}\text{Ni}$ :	$^{62, \underline{63}, 64}\text{Ni}$ , $^{63, \underline{64}}\text{Cu}$ , $^{64, \underline{65}, 66}\text{Zn}$
(2)	$^{79}\text{Se}$ :	$^{78, \underline{79}, 80}\text{Se}$ , $^{79, \underline{80}, 81}\text{Br}$ , $^{80, \underline{81}, 82}\text{Kr}$
(3)	$^{85}\text{Kr}$ :	$^{84, \underline{85}, \underline{85m}, 86}\text{Kr}$ , $^{85, \underline{86}, 87}\text{Rb}$ , $^{86, \underline{87}, 88}\text{Sr}$
(4)	$^{95}\text{Zr}$ :	$^{94, \underline{95}, 96}\text{Zr}$ , $^{95, \underline{96}, 97}\text{Mo}$
(5)	$^{99}\text{Tc}$ :	$^{98, \underline{99}}\text{Tc}$ , $^{99, \underline{100}}\text{Ru}$
(6)	$^{134}\text{Cs}$ :	$^{132, \underline{133}, 134}\text{Xe}$ , $^{133, \underline{134}, \underline{135}}\text{Cs}$ , $^{134, \underline{135}, \underline{136}}\text{Ba}$
(7)	$^{148}\text{Pm}$ :	$^{146, \underline{147}, 148}\text{Nd}$ , $^{147, \underline{148}, \underline{149m}}\text{Pm}$ , $^{147, \underline{148}, 149, \underline{150}}\text{Sm}$
(8)	$^{151}\text{Sm}$ :	$^{150, \underline{151}, 152}\text{Sm}$ , $^{151, \underline{152}, 153, \underline{154}}\text{Eu}$ , $^{152, \underline{153}, \underline{154}, 155}\text{Gd}$
(9)	$^{163}\text{Ho}$ :	$^{163, \underline{164}}\text{Dy}$ , $^{163, \underline{164}, 165}\text{Ho}$ , $^{164}\text{Er}$
(10)	$^{170}\text{Tm}$ :	$^{168, \underline{169}, 170}\text{Er}$ , $^{169, \underline{170}, \underline{171}}\text{Tm}$ , $^{170, \underline{171}, 172}\text{Yb}$
(11)	$^{176}\text{Lu}$ :	$^{174, \underline{175}, 176}\text{Yb}$ , $^{175, \underline{176m}, \underline{176}}\text{Lu}$ , $^{176, \underline{177}}\text{Hf}$
(12)	$^{179}\text{Hf}$ - $^{179}\text{Ta}$ :	$^{179, \underline{180}, \underline{181}, \underline{182}}\text{Hf}$ , $^{179, \underline{180}, \underline{180m}, \underline{182}}\text{Ta}$
(13)	$^{185}\text{W}$ :	$^{184, \underline{185}, 186}\text{W}$ , $^{185, \underline{186}, 187}\text{Re}$ , $^{186, \underline{187}, 188}\text{Os}$
(14)	$^{192}\text{Ir}$ :	$^{190, \underline{191}, 192}\text{Os}$ , $^{191, \underline{192}, 193}\text{Ir}$ , $^{192, \underline{193}, 194}\text{Pt}$
(15)	$^{204}\text{Tl}$ :	$^{203, \underline{204}, 205}\text{Tl}$ , $^{204, \underline{205}, 206}\text{Pb}$

overlined: s-only stable nuclei  
underlined: unstable nuclei:

**bold**: main branching

*italic*: EC,  $\beta^+$ ,  $\beta^-$  competition  
**m**: isomer population

# Level Densities

# Level Density in Macroscopic-Microscopic Approach

Total level density  $\rho$  from Fermi-Gas model with evenly distributed parities.

$$\begin{aligned}\rho(U, J, \pi) &= \frac{1}{2} f(U, J) \rho(U) \\ \rho(U) &= \frac{1}{\sqrt{2\pi}} \frac{\sqrt{\pi}}{12a^{1/4}} \frac{\exp(2\sqrt{aU})}{U^{5/4}} \\ f(U, J) &= \frac{2J+1}{2\sigma^2} \exp\left(\frac{-J(J+1)}{2\sigma^2}\right) \\ \sigma^2 &= \frac{\Theta_{\text{rigid}}}{\hbar^2} \sqrt{\frac{U}{a}} \quad \Theta_{\text{rigid}} = \frac{2}{5} m_u A R^2 \quad U = E - \delta\end{aligned}$$

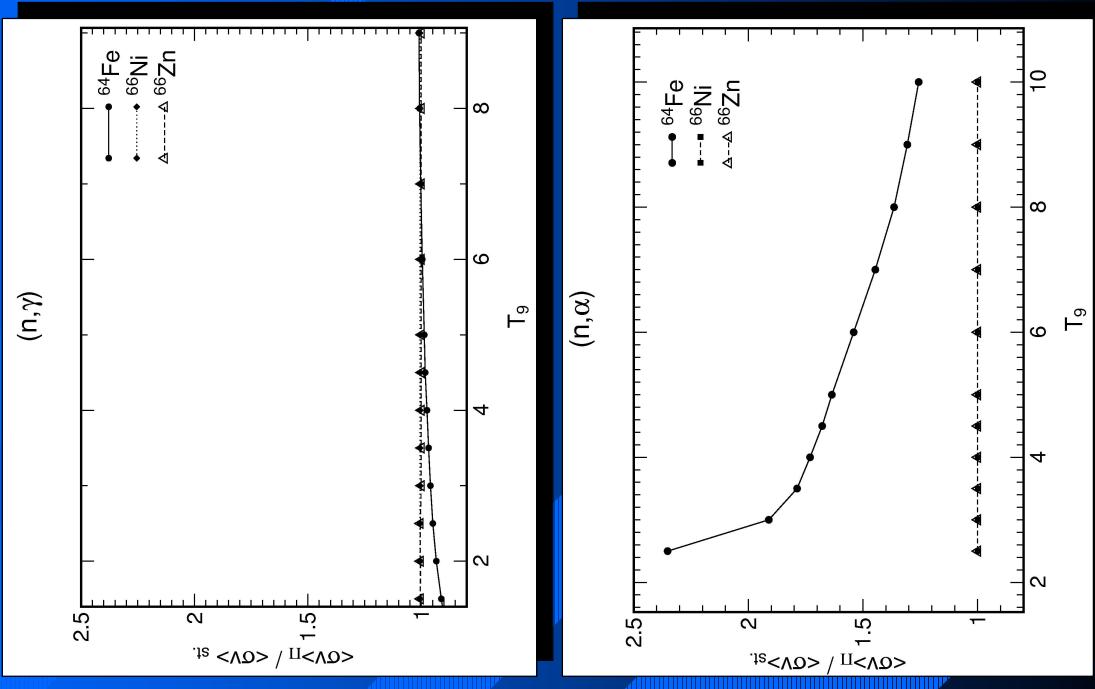
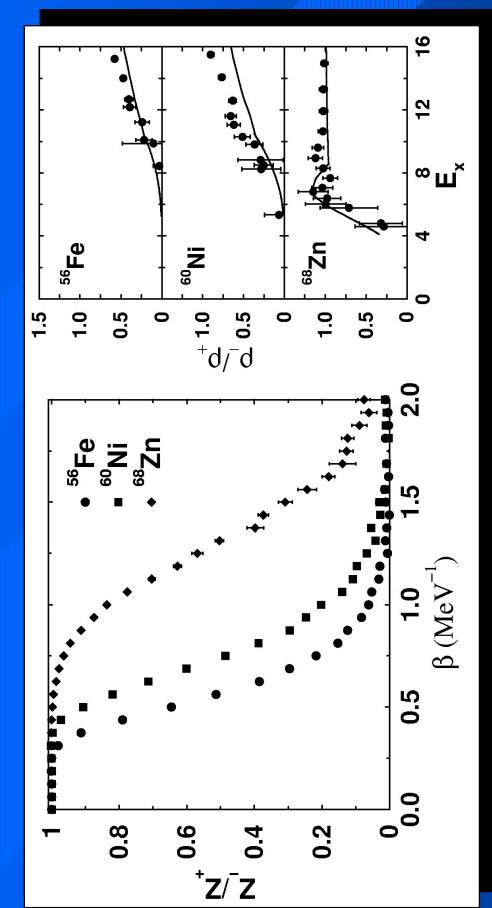
## Microscopic Corrections:

- 
- 1. Shell- and deformation effects
- 
- 2. Pairing effects

$$\delta(Z, N) = \Delta_n(Z, N) + \Delta_p(Z, N)$$

$$\begin{aligned}\Delta_n(Z, N) &= \frac{1}{4} [EG(Z, N-2) - 3EG(Z, N-1) + \\ &\quad + 3EG(Z, N) - EG(Z, N+1)]\end{aligned}$$

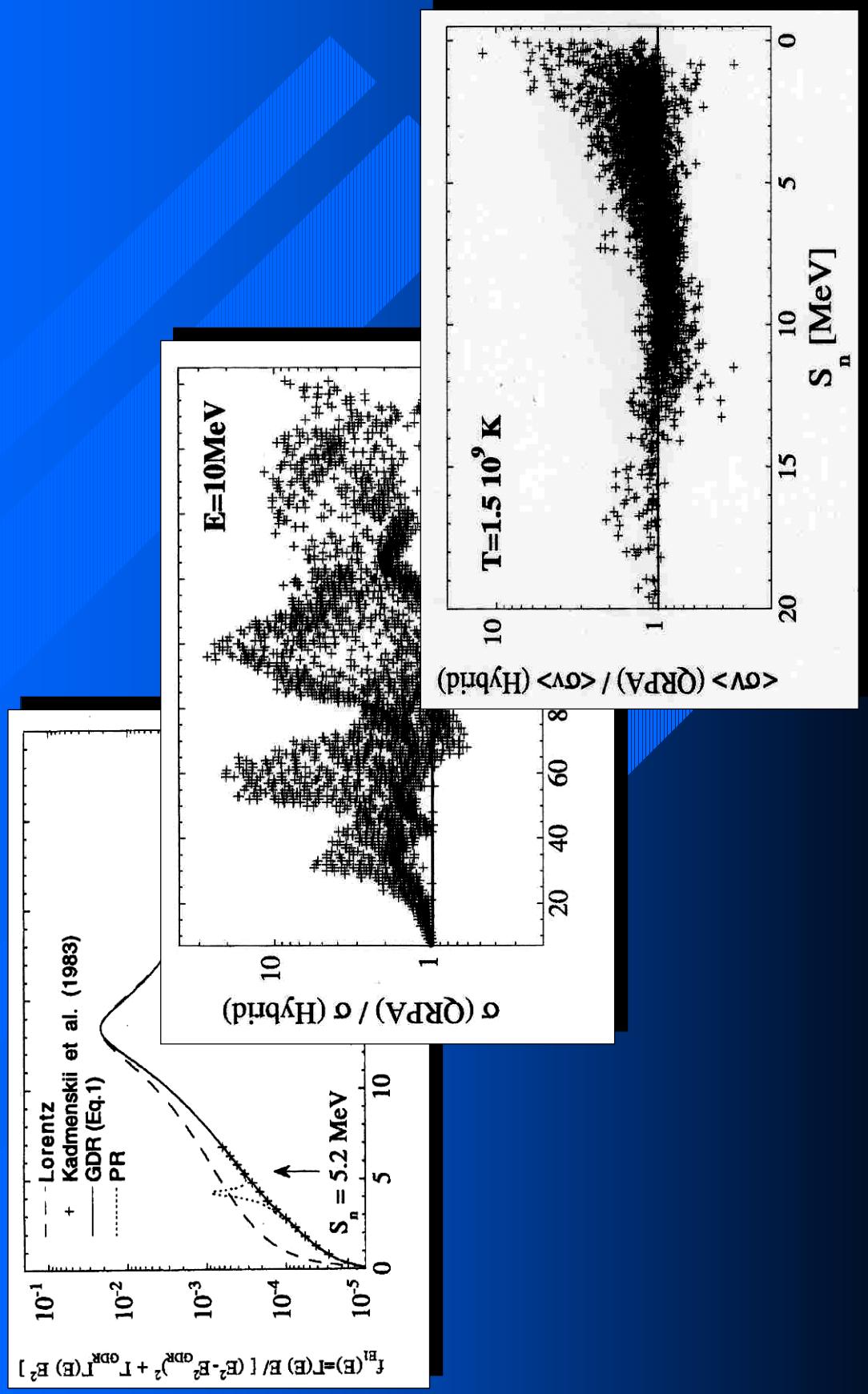
# Influence of a Realistic Parity Distribution



# Pygmy Resonances?



# Possible Impact of Pygmy Resonance



Goriely & Khan 2003

# Conclusions

- Large number of nuclei, also off stability
  - Global theoretical models necessary
- Low interaction energies
  - Interplay of different reaction mechanisms (HF, RC, DC)
    - » Global Hauser-Feshbach models work well
    - » RC, DC (DWBA) more sensitive to nuclear structure, large uncertainties
  - Measurements in relevant energy range absolutely necessary!
- Indirect methods partially successful
  - Trojan horse method for light targets (Baur et al.) in H-burning
  - (d,p) Reactions
    - » info about low-lying states, spectroscopic factors for DC
    - » optical potential for capture reaction?
- Other methods can provide important information to test predictions although they access only few of the relevant channels/transitions
  - » However: only partial information  $\Rightarrow$  theory needed to calculate desired rate!

# Experimental Requirements in Nuclear Astrophysics I

- Specific important reactions (examples)
  - $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ ,  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ , ... (new methods?)
  - Reactions in diff. burn. stages, s-Process branchings
  - Quenched magicity? (r-process)
  - p-Dripline (rp-Process)
- Systematics (comparison with theory)
  - At stability:
    - » Level density, GDR, optical  $\alpha$ -potentials
    - » Resonance parameters, interference of reaction mechanisms
    - » Completion of decay schemes
    - » Fission properties (fission barriers, products)

# Experimental Requirements in Nuclear Astrophysics II

- Systematics (part II)
  - Far off stability:
    - » Masses
    - » Half-lives
    - » Level schemes, etc.
    - » + see above...
- Simple, fast access to results (uniformly defined formats for data and derived quantities)